DEVELOPMENT OF A PRE-SCREENING METHODOLOGY TO AID IN DETERMINING POTENTIAL ENERGY SAVINGS IN COMMERCIAL BUILDINGS

A Thesis

by

DAVE C. HICKS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Mechanical Engineering

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Approved by:

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Committee Members,	Charles Culp
	W. Dan Turner
Head of Department,	Dennis O'Neal

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ABSTRACT

Development of a Pre-Screening Methodology to Aid in Determining Potential Energy Savings in Commercial Buildings. (December 2008)

Dave C. Hicks, B.S., Texas A&M University

Chair of Advisory Committee: Dr. David E. Claridge

This thesis presents a methodology developed to aid in the determination of potential sources and the potential scale of energy savings in commercial buildings. As a pre-screening tool, the methodology is designed to serve as the first analysis of the building's potential for energy savings using limited data prior to a site visit. A Microsoft® Excel-based tool was developed to perform this analysis semi-automatically with user operation. A fundamental concept used in this methodology is that of the energy balance load, defined as heating plus electricity minus cooling.

The methodology is designed to require only historical weather data, historical whole-building energy consumption data, the total conditioned floor area, and the basic function of the building. Upon following a short procedure developed and outlined in this thesis, this limited data yields information that can lead to conclusions about the building's energy consumption. The output information includes estimates of a major building thermal parameter—the building's overall heat transfer coefficient including the total outside air flow rate into the building. In addition to providing this information, the Excel tool includes already-formatted plots of the energy consumption commonly used in energy analysis. These include cooling, heating, and electricity vs. both outside air temperature and time.

Three case studies illustrate the utility of this methodology. The calculated energy balance load—calculated using parameters determined through this methodology—yielded values on average within 5.4% of measured values.

To Julie, my miracle wife

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

This chapter includes the motivation for the research presented in this thesis, the objectives of the research, and a description of the following chapters.

Objectives

The purpose of this research is to develop a self-contained pre-screening methodology for determining the potential scale and sources of energy conservation in commercial buildings. This pre-screening method would achieve several noteworthy objectives. First, it would be distinct from other methods by using the energy consumption data of only the building under investigation—that is, it would not be fundamentally dependent upon comparison to other buildings.

Second, it would help to reduce the time and efforts of those who further investigate the energy conservation opportunities by estimating building parameters, such as the combined overall heat transfer coefficient and outside air ventilation flow rate. These parameters and characteristics are not easily attainable by any current pre-screening method.

Third, this method would help to automate the pre-screening process by providing spreadsheet tools and programs that guide the user in estimating building

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This thesis follows the style of *ASHRAE Transactions*.

parameters and characteristics. This reduces the subjectivity involved in estimating parameters based on past experience and makes the pre-screening process more straightforward for less experienced engineers.

Finally, the accomplishment of the second and third objective would consequently reduce the expense of performing an energy assessment by reducing the time spent both in the initial analysis and during the site visit. Time would be saved in the initial analysis via use of the semi-automated tools rather than laboriously manipulating data manually.

Motivation

Of approximately 426 quadrillion Btu of energy consumed by the world in 2003, about 98 quadrillion were consumed in the United States. About 6.6% of U.S. energy consumption, or 6.5 quadrillion Btu, were consumed by commercial buildings for a total cost of almost $108 billion. The commercial building energy consumption increases to 13.7 quadrillion Btu when losses due to the generation, transmission, and distribution of the electricity consumed by commercial buildings are included (EIA 2006, EIA 2007).

With such a massive amount of energy being used in buildings, and with rising energy prices and a growing awareness of the potential effects of energy consumption on the environment, building owners are increasingly becoming interested in more efficient building operation. One way energy savings may be realized is by retrofitting and

Continuous Commissioning® (CC®)[1], for which typical savings are 15-25% (Liu et al. 1997, Turner et al. 1996). The first step in the CC process—and the focus of this research—is a CC Assessment. CC is described in more detail in Chapter II.

Description of Chapters

This thesis is comprised of six chapters, references, appendices, and a vita. Chapter I introduces the thesis and gives the objectives of and motivation for the research.

A literature review of existing practices and methods for pre-screening commercial buildings for potential energy savings is presented in Chapter II. It is divided into sections on Continuous Commissioning, high-level energy audits, and pre-screening methods. The first section describes the origin of CC, the CC process, and the successes and distinctions of CC. The remaining sections describe and discuss three high-level energy audit methods and ten pre-screening methods grouped into four categories. High-level audit methods presented are the pre-site analysis, the information-based audit, and the walk-through assessment. Pre-screening methods include uses of energy consumption regression, expert systems, indices, and simulation. Chapter III describes the steps taken to develop the pre-screening methodology. The first step is to determine what to include in the pre-screening analyses. The second step is to develop a methodology that considers the included parameters and characteristics.

[1] Continuous Commissioning and CC are registered trademarks of the Texas Engineering Experiment Station. To improve readability, the trademark symbol will not always be used.

The third and final step is to test the pre-screening methodology on a sample set of buildings and evaluate the results. The first two of these three steps are included in Chapter III.

Chapter IV illustrates the tools used in the pre-screening methodology and also the actual procedure to be followed in the performance of the pre-screening. The three steps of the procedure are described in detail, along with the tools used in each step.

Chapter V presents and discusses the results of applying the pre-screening methodology to three buildings. The results achieved by this methodology are compared to the conclusions made through more detailed CC assessments or site observations. Similarities and differences are noted and discussed.

A summary of the research performed and conclusions comprise Chapter VI. This is followed by references and a vita.

CHAPTER II

LITERATURE REVIEW

Introduction

Previous work applicable to this research deals with Continuous Commissioning, high-level audits, and pre-screening methods. A description of CC, its successes, and its distinctions from typical commissioning and energy audit methods are presented here. Three high-level audit methods and ten pre-screening methods grouped into four categories are examined here, and their relevance and limitations are described. The high-level audit methods noted are the pre-site analysis, the information-based audit, and the walk-through assessment; pre-screening methods include uses of energy consumption regression, expert systems, indices, and simulation.

Energy audits, which generally result in retrofit recommendations, fall into one of three categories of increasing complexity: the walk-through assessment, the energy survey and analysis, and the detailed analysis of capital-intensive modifications (ASHRAE 2003, Mazzucchi 1992). The level of audit performed would depend upon the degree of accuracy desired and the resources of the building owner. Only the walk-through assessment, requiring the least amount of time and effort, may be considered to be high-level; the other two are not applicable to this research.

Though several pre-screening methods exist to determine the viability of saving energy in a building and even the potential measures to produce those savings, the only one identified in this review capable of doing so without comparison with other buildings was developed by Baltazar-Cervantes (2006). But this method, described in detail below, was found to overestimate potential savings by as much as seven times those expected based on a full audit.

Continuous Commissioning

Continuous Commissioning was developed in the mid-1990's. It began by using long-term hourly measurements along with site visits and an engineering analysis to determine if buildings that had already been retrofitted were operating efficiently. This method contrasted with the prevailing method of identifying operation and maintenance (O&M) improvements by a walk-through assessment in the energy audit process (Liu et al. 1994b). CC was then applied to buildings that had not been previously retrofitted and has evolved into a "comprehensive ongoing process to resolve operating problems, improve comfort, optimize energy use and identify retrofits for existing commercial and institutional buildings and central plant facilities" (Claridge et al. 2000, Liu et al. 2002). It is different from typical commissioning as described in ASHRAE Guideline 1-1996 because its aim is optimizing a building for its current usage and needs rather than commissioning to its original design intent, and CC should be done on a continuing basis (ASHRAE 1996, Claridge et al. 2000, Verdict 2006).

The CC process is divided into two phases. The first phase consists of two steps: (1) identify buildings or facilities and (2) perform CC assessment and develop project scope. The second phase includes six steps: (1) develop the CC plan and form the project team, (2) develop performance baselines, (3) conduct system measurements and develop CC measures, (4) implement CC measures, (5) document comfort improvements and energy savings, and (6) keep the commissioning continuous. The first phase is the focus of the proposed research. It is after this phase that a contract is signed based on estimated energy savings from preliminary CC measures and the estimated cost of carrying out these measures (Liu et al. 2002, Liu et al. 2003).

Continuous Commissioning has proven to be very successful in both retrofitted and unretrofitted buildings. Numerous case studies, including those presented by Claridge et al. (1994, 1996), Liu et al. (1994a, 1994b), and Wei et al. (2001) show that CC savings average about 20% of the total building energy cost on top of retrofit savings; CC was often found to provide as much or more savings than retrofits (Turner et al. 1996). Typical savings of 25% of the total energy cost were achieved by using existing HVAC and control systems in buildings (Liu et al. 1997). A ten-year implementation of CC on the Texas A&M University campus yielded \$35 million in measured savings at a cost of \$7 million (Deng et al. 2006). With little or no capital investment required, CC yields a high rate of return with paybacks typically under two years (compared to, for example, two to five years for a lighting retrofit) at a cost of \$0.25 to \$0.50 per square foot of conditioned space. For this reason, CC can lower the total project payback for an energy improvement project involving retrofit and CC measures (Verdict 2006).

CC should be performed prior to a retrofit so that the retrofit's true cost effectiveness may be determined with an improved energy consumption baseline developed in the CC process. In some cases, CC may even preclude a retrofit by making it either unnecessary or cost-ineffective (Turner et al. 1996). For these reasons, the current research was targeted specifically for use in CC.

High-Level Energy Audits

Hoshide (1995) breaks down an effective energy audit into pre-site work, the on-site energy audit, and post-site work. He specifies a rather detailed list of information that should be gathered prior to visiting a building: (1) previous energy audit information, (2) design standards and codes, (3) design and as-built drawings of energy-using systems, (4) equipment documentation and operating schedules, (5) plug load equipment, (6) occupancy schedules, (7) O&M documentation, (8) future building plans, and (9) twelve months of utility data with rate schedules. Based on the type of building, the energy use intensity (EUI—total energy use divided by gross floor area), and the expertise of the auditor, an initial energy conservation measure (ECM) and O&M list would be developed. This pre-site work is similar to a pre-screening in that both are designed to be preliminary assessments with more detailed analysis to follow. The pre-screening methodology presented in this thesis, however, would require much less information and documentation—only total building conditioned floor area and item (9) above, along with corresponding historical weather data.

The success of a walk-through assessment similarly depends upon the expertise of the auditor. Upon analyzing energy bills and briefly examining the building, the auditor may determine how much energy may be saved and at what cost. Also, potential capital improvements may be identified (ASHRAE 2003). The pre-screening methodology presented here does not require auditor expertise or a site visit.

The information-based audit, which is an evaluation of information gathered remotely, may or may not lead to further analysis and results in general recommendations without much detail (Landman 1998). Unlike this type of audit, the pre-screening methodology presented here is designed to aid in the identification of more building-specific potential energy savings opportunities to be further investigated.

Pre-Screening Methods

Energy consumption regression

The PRInceton Scorekeeping Method (PRISM) model was first developed by Fels (1986) to measure energy performance changes of residential buildings. Reynolds et al. (1990) define a pre-screening methodology that uses PRISM models to find energy-efficiency opportunities in small commercial buildings. In this methodology, three models—PRISM CO (Cooling Only), PRISM HO (Heating Only), and PRISM HC (Heating and Cooling)—are applied to monthly energy consumption data of small commercial buildings.

The models essentially analyze energy consumption plotted against outside air temperature and perform a three-parameter change-point regression. A “good” fit of the PRISM CO, PRISM HO, or PRISM HC model indicates whether the modeled energy source is primarily used for cooling, heating, or heating and cooling, respectively. The PRISM CO model assumes a three-parameter change-point profile when energy consumption is plotted against outside air temperature in which the energy consumption is weather-independent (relatively flat) below a "reference temperature" and is linear with a positive slope above the reference temperature. The reverse is true for the PRISM HO model, and a combination of these is true for the PRISM HC model. A poor fit by all three PRISM models indicates either erroneous data, which may be "fixed" manually based on pattern recognition, or weather-independent consumption. (Reynolds et al. 1990)

The usefulness of these models as a pre-screening method lies in the matching of energy sources to major end uses—cooling, heating, or weather-independent base load. The relative size of each end use may then be determined, but any conclusions about the potential savings must be made based solely upon other analyses, a site visit, and the expertise of the auditor. Another weakness of this method is that it may not be able to distinguish heating and cooling from process loads—defined in this thesis as energy consumption that does not contribute to building heating or cooling needs. Also, this method's inability to account for simultaneous heating and cooling leads to inflated base loads and diminished heating and cooling estimates.

Expert system

There have been at least two attempts at developing a pre-screening expert system to simulate expert energy auditors' decision-making process. Gatton et al. (1995) developed a three-phase system. The first phase compares the building's annual energy cost index (ECI—total energy cost divided by gross floor area) with a comparative value that depends on building systems operating hours, the number of months per year that the building is occupied, and the building location's climate. If the building has relatively high energy use, it warrants further investigation in phase two, which asks the user questions applicable to a selected energy system. Phase two's interactive decision tree is based upon a knowledge base extracted from interviews with energy engineering experts. The experts reviewed and refined the decision tree's rules and conclusions by noting incorrect conclusions, conclusions made with insufficient supportive evidence, missing rules, and areas needing more in-depth analysis. Phase two results in a list of potential retrofit measures recommended for cost/benefit analysis in phase three.

A limitation of this method is that the expert system considers only retrofits for potential energy savings rather than operational and control changes. Another shortcoming is that phase one uses degree days to represent the building location's climate rather than actual weather data for the time period during which energy consumption was measured. Also, the first phase uses only one index—the ECI—to make a judgment on the building's candidacy for energy savings.

The second expert system, the Building Energy Auditing Management Expert System (BEAMES), was built for residential buildings in Europe. It includes a pre-audit phase and a guide for measurement techniques, audit procedures, and analysis techniques. The pre-audit phase uses an unspecified "small amount of information" about the building that can be gathered by non-technical people to develop initial conclusions about the complexity and cost of a full audit and to provide a list of potential

ECMs. BEAMES essentially uses statistics and a neural network pattern associator to compare the building being audited to similar buildings in a sample building set and then suggest similar ECMs. The neural network contains neuron-like processing elements, called units, that interact with each other via weighted connections. Each unit has inputs, either information from the user or outputted conclusions from other units, that are weighted in importance for use in that unit's process. The system can be "trained" by inputting previously audited building data and the corresponding output so that it produces similar conclusions the next time it analyzes similar input (Caudana et al. 1995).

Besides the fact that BEAMES is for residential buildings, there is a fundamental difference in this method and the one presented in this thesis. Because the BEAMES knowledge base is a sample set of buildings, its conclusions are only correct if the conclusions about the sample set of buildings are correct. The proposed research, however, will function as a stand-alone analysis (not requiring data from other buildings). This means that incorrect conclusions and limited success in previously audited buildings need not be perpetuated in future analyses via an expert system coming to the same incorrect conclusions as before.

Indices

Indices that can be derived from basic building and energy use data may be used as normalizing factors to compare building energy performance and thereby determine a building's potential for energy savings. A general approach is to use annual EUI and

ECI (ASHRAE 2007). Care must be taken when benchmarking a building's EUI to that of a set of buildings, however. In one study of office buildings, Sharp (1996) found that average and median EUIs for each of the nine U.S. regional census divisions in the 1992 Commercial Buildings Energy Consumption Survey (CBECS) database were not reliable comparators for localized EUIs. He posited that a better assessment of a building's energy performance can be obtained by a comparing its EUI to an EUI predictive model that accounts for the CBECS variables he statistically determined to be the most significant determinants of EUI (other than floor area)—number of workers, number of computers, owner-occupancy, operating hours, and the presence of an economizer or chiller. Sharp later performed a statistical analysis on EUI determinants and developed an EUI predictive model for public schools (Sharp 1998).

Gardiner et al. (1984) compiled a database of the energy savings and cost-effectiveness of conservation projects in 311 commercial buildings to provide a reference for predictions of energy savings and cost in future projects. EUI was used to record pre- and post-retrofit energy performance. The cost-effectiveness was recorded with indices such as project cost per square foot, project cost per unit energy saved, and simple payback times.

Haberl and Komor (1990a) discussed the utility of annual and monthly indices as pre-screening indicators that could direct auditors to problems during the site visit. Indices examined include EUI and ECI, peak electric demand per square foot, monthly electric load factors (ELF—electric use for a period [kWh] divided by the product of the peak electric demand in the period [kW] times the time in the period [h]), monthly occupancy load factors (OLF—occupied hours divided by total hours in a period), PRISM analysis results, and an index that evaluates electricity usage during unoccupied periods. EUI and ECI are used as benchmarking indices to be compared to a database. Comparison of the ELF and the OLF yields information about electricity usage during unoccupied periods. For example, if the ELF is greater than the OLF, the building is likely to be consuming electricity while unoccupied. The PRISM analysis yields three parameters—the base load, the reference temperature, and the slope of the consumption above the reference temperature—that make up the normalized annual consumption (NAC) index. These values can indicate the portion of energy used for heating or cooling versus weather-independent base loads.

Haberl and Komor (1990b) also considered what indications may be gleaned from daily and hourly indices. The power level (electric demand per square foot) was considered during occupied and unoccupied periods. Cooling-related power level (obtained by determining base loads with a PRISM analysis) was compared with recommended lighting power for particular building types. Daily maximum and minimum temperatures were recorded to determine if thermostatic control was set correctly and if setbacks were being implemented during unoccupied periods. Load shapes were also examined and conclusions were formed based on the experience of the auditor. They concluded that commercial building energy audits should be multi-level analyses that allow the auditor to interact with the process rather than prescriptive, fill-in-the-blank assessments.

Landman (1998) used existing indices, such as EUI, ELF, and OLF, and developed new indices to improve initial energy analysis of K-12 public schools for the purpose of determining potential energy savings. Benchmarking with other buildings and comparison of different indices for the same building to each other provide information about the building's energy performance compared to other buildings and the building's operational changes by occupancy schedule. He found that schools are better modeled by separating data into unoccupied summer months and occupied school-year months.

Sharp's (1996) conclusions support the self-containment approach of the pre-screening methodology presented in this thesis that does not fundamentally require benchmarking against buildings that may be too dissimilar for valuable comparison. Haberl and Komor's (1990b) conclusions support the pre-screening methodology in that its results are to be an aid for a more in-depth analysis to be conducted by engineers with expertise. It should be noted that the proposed pre-screening methodology is designed to provide engineers with useful information for future analysis, not replace the need for knowledgeable engineers.

Simulation

Zhu (2005) developed a novel methodology to pre-screen commercial buildings for potential energy savings based on comparing a building's energy consumption to that of a simulated typical building of the same size with the most efficient heating, ventilation, and air conditioning (HVAC) system. It is designed to require only utility bills, building total floor area, and weather data.

The first step in the four-step process is testing the utility bills to determine if they include both weather-dependent and weather-independent loads. If both load types are present, the second step separates the two based on thermal balance. In the third step, a fuzzy logic application uses the weather-dependent loads to identify the main type of HVAC system in the building. Testing this step on 40 buildings resulted in 18 correctly identified HVAC systems. The method considered eight HVAC system types and assumed that the whole buildings used the same type of system, so understandably buildings that contain more than one HVAC system are not well-suited for this analysis. The fourth step estimates potential energy savings and then recommends further analysis via an energy audit if appropriate.

The most significant difference between Zhu's methodology and the one presented here is that the former makes many assumptions based on what is "typical" for commercial buildings in the 1999 CBECS (EIA 2002). Assumed parameters include the number of floors based on rough estimations of averages for reported groups (e.g., 15 as the average number of floors for buildings reporting "ten or more" floors), occupancy concentration, outside air flow rate, window-to-wall ratio, and heat transfer coefficients for walls, windows, and roofs (Zhu 2005). Atypical buildings, especially those with more than one HVAC system, consequently do not perform well with this method.

Baltazar-Cervantes (2006) developed a rigorous pre-screening methodology that involves automatically calibrating a detailed model of a building and then conducting a multi-level, exhaustive optimization process that finds the lowest-cost HVAC operation for a range of weather bins. The purpose was to determine potential energy savings by comparing actual energy use with optimized energy use. Energy savings predicted by this method were an average of 4.9 times the audit-expected savings and 3.3 times the measured savings in three of four test buildings (Baltazar and Claridge 2007, Baltazar-Cervantes 2006).

Summary

In conclusion, several methods exist to provide high-level information for the purpose of determining potential energy savings in buildings. Existing methods require various amounts of input information and use different approaches in generating conclusions about a building's energy performance. There remains a need for a pre-screening methodology that uses easily obtained information and does not fundamentally depend upon comparison to other buildings or the expertise of the user.

CHAPTER III

DEVELOPMENT OF THE PRE-SCREENING METHODOLOGY

Introduction

To accomplish the objectives of this research, a procedure to be applied to building energy consumption data for use in the Continuous Commissioning process must be defined. The results of the procedure are then to serve as aids in future analysis of the building. In this chapter, the development of the pre-screening methodology and a description of its procedure are presented.

Developing the pre-screening methodology consisted of three main steps: (1) determine the set of parameters, indices, or attributes to consider that would be useful in further analysis; (2) develop a pre-screening procedure that considers these items and tools with which to perform the procedure; and (3) apply procedure to a sample set of buildings and evaluate results. Many iterations of these steps were performed as the pre-screening methodology was evaluated and refined to its current state.

The first of these three steps is described in the next section. The energy balance method used in developing a pre-screening procedure is then explained in detail in the following section of this chapter. A chapter summary concludes this chapter. The actual procedure itself and the tools with which to perform the procedure are covered in Chapter IV, while the results of applying this procedure to a sample set of buildings are discussed in Chapter V.

Parameters to be Determined

Many parameters would be useful in further analysis in the CC process, but most require site visits in order to obtain them. Two very important parameters that normally require a set of plans and/or a site visit to obtain are a building's overall heat transfer coefficient, UA_{tot}, and the outside air ventilation flow rate, $\dot{V}_{oa}$. This thesis develops a method for determining the total heat transfer coefficient of a building in combination with the outside air ventilation flow rate, $UA_{tot} + \rho c_p \dot{V}_{oa}$, using only limited measured energy consumption data.

Development of Energy Balance Approach

The goal of the pre-screening procedure is to provide the information outlined above using limited information about the building. To accomplish this, a mathematical model of a building was built that equates relatively easily obtained energy consumption data with loads calculated to require the measured energy consumption. The model used for this pre-screening methodology is based upon the first law of thermodynamics, also known as the conservation of energy principle, which states that the net change in energy of a system during a process is equal to the difference between the total energy entering and the total energy leaving a system during that process (Cengel 2007). This may be stated mathematically as

$$E_{in} - E_{out} = \Delta E_{system}, \tag{1}$$

where

E_{in} = total energy entering the system,

E_{out} = total energy leaving the system, and

ΔE_{system} = change in total energy of the system.

For this thesis, a building is considered to be an open system in a steady state condition, where there is no change in energy for the time increment under consideration. To utilize this simplified model, several assumptions are made that hold true for each increment of time under consideration:

1) Room temperature may be modeled as a constant average value.
2) Heat added or removed may be considered to be added or removed at a constant average rate.
3) Mass flow rate into and out of the building may be modeled with a constant average flow rate.
4) Outside air temperature and relative humidity may be modeled with constant average values.

Since the building model is in steady state, the first law of thermodynamics requires that

$$E_{in} - E_{out} = 0. \tag{2}$$

Energy may be transferred by heat, mass, or work. There is no work done on a building or by the building, but there are several sources of energy transfer by heat and mass flow. Heat transfer sources include heating and cooling return air through HVAC equipment, gains from electric lights and equipment, gains or losses by conduction through the building envelope, gains from occupants, and solar gains through both windows and walls. Mass transfer occurs through outside air ventilation and infiltration (assumed to be part of the ventilation in this model). Combining these energy transfer methods, the system may be expressed as

$$Q_H - Q_C + fQ_{ele} + Q_{env} + Q_{vent} + Q_{inf} + Q_{occ} + Q_{sol} + Q_{ts} = 0, \qquad (3)$$

where

Q_H	=	heating energy provided by HVAC equipment,
Q_C	=	cooling energy provided by HVAC equipment,
f	=	fraction of whole-building electricity that turns to heat inside the building envelope,
Q_{ele}	=	whole-building electricity use,
Q_{env}	=	energy transfer by conduction through building envelope,
Q_{vent}	=	energy transfer through outside air ventilation,
Q_{inf}	=	energy transfer through infiltration,
Q_{occ}	=	sensible energy gain from occupants,
Q_{sol}	=	solar energy gain through windows,
Q_{ts}	=	solar energy gain through opaque surfaces.

If infiltration loads are assumed to be nonexistent or part of the ventilation load, the infiltration term is eliminated from Equation (3). Because gain due to occupants is generally difficult to calculate with the limited building information available at the pre-screening stage and because it is a small portion of the overall HVAC load, it is eliminated. The relatively small impact of solar gains on the overall HVAC load and the time, effort, and amount of building information required to calculate them also warrant exclusion from Equation (3). Performing the Simplified Energy Analysis Procedure (ASHRAE 1984) on two buildings to compute the occupancy and solar gains showed that the combined effect of these loads accounted for less than 5% of the building's entire load. Excluding these loads from Equation (3) results in

$$Q_H - Q_C + fQ_{ele} + Q_{env} + Q_{vent} = 0. \tag{4}$$

These exclusions are warranted by the simple fact that their inclusion would be beyond the scope and objectives of this pre-screening methodology because of the time, effort, and information required to compute them.

Rearranging Equation (4) to group terms that can be easily measured on the left side and terms that are not readily available on the right side results in

$$Q_H - Q_C + fQ_{ele} = -Q_{env} - Q_{vent}. \tag{5}$$

Substituting

$$Q_{env} = UA_{tot}(T_{oa} - T_{rm}) \tag{6}$$

$$Q_{vent} = \rho c_p \dot{V}_{oa}(T_{oa} - T_{rm}) \tag{7}$$

into Equation (5) yields

$$Q_H - Q_C + fQ_{ele} = \left(UA_{tot} + \rho c_p \dot{V}_{oa}\right)(T_{rm} - T_{oa}), \tag{8}$$

where

UA_{tot}	=	building overall heat transfer coefficient,
ρ	=	density of air,
c_p	=	specific heat of air at constant pressure,
$\dot{V}_{oa}$	=	outside air flow rate,

T_{rm} = room temperature, and

T_{oa} = outside air temperature.

The energy balance so far has included only sensible energy, but there also exists a balance of latent energy given by

$$-Q_{C,lat} + \left[Q_{vent,lat} + Q_{int,lat}\right]^{+} = 0, \tag{9}$$

where

$Q_{C,lat}$ = latent cooling energy provided by HVAC equipment,

$Q_{vent,lat}$ = latent cooling load due to outside air ventilation,

$Q_{int,lat}$ = latent cooling load due to latent heat generated inside building,

and the plus sign superscript indicates that the bracketed expression is included only if it is positive. This is used because it is assumed that latent energy is only removed by HVAC equipment rather than added to, and consequently the HVAC cooling term in Equation (9) must be negative or zero. Substituting

$$Q_{vent,lat} = \rho h_{fg} \dot{V}_{oa}(w_{oa} - w_{cl}) \tag{10}$$

$$Q_{int,lat} = (1 - X_{oa}) q_{i,lat} \tag{11}$$

into Equation (9) and rearranging produces

$$Q_{C,lat} = -\left[\rho h_{fg} \dot{V}_{oa}(w_{oa} - w_{cl}) + (1 - X_{oa}) q_{lat}\right]^{+}, \tag{12}$$

where

h_{fg} = enthalpy of vaporization of water,

w_{oa} = specific humidity ratio of outside air,

w_{cl} = maximum specific humidity ratio of air leaving cooling coil.

X_{oa} = $\frac{\dot{V}_{oa}}{\dot{V}_{tot}}$ = outside air fraction of total air flow rate, $\dot{V}_{tot}$, and

q_{lat} = total latent heat generated inside building (some of which is exhausted).

Adding the latent energy balance, Equation (12), to the sensible energy balance, Equation (8), results in a key equation for the pre-screening methodology:

$$\begin{aligned} Q_H - Q_{C,tot} + fQ_{ele} = {} & \left(UA_{tot} + \rho c_p \dot{V}_{oa}\right)(T_{rm} - T_{oa}) \\ & -\left[\rho h_{fg} \dot{V}_{oa}(w_{oa} - w_{cl}) + (1 - X_{oa})q_{lat}\right]^{+} \end{aligned} \tag{13}$$

where $Q_{C,tot}$ is the total cooling energy, both sensible and latent, provided by HVAC equipment. An important advantage in using the energy conservation approach described here is that it is true for every HVAC system type, and therefore Equation (13) is applicable to every building.

If temperatures are in °F, air flow rates are in cfm, and heating and cooling are in Btu/hr, the products ρc_p and ρh_{fg} may be simplified by assuming constant properties over expected temperature ranges:

$$\rho c_p = (0.075\ lb/ft^3)\left(0.24\ \frac{Btu}{lb \cdot \text{°F}}\right)(60\ min/hr) = 1.08\ \frac{Btu/hr}{cfm \cdot \text{°F}} \tag{14}$$

$$\rho h_{fg} = (0.075\ lb/ft^3)\left(1075\ \frac{Btu}{lb}\right)(60\ min/hr) \approx 4840\ \frac{Btu/hr}{cfm}. \tag{15}$$

These products will be written as simply 1.08 and 4840 for the remainder of this thesis.

Equation (13) contains four terms on the left-hand side, three of which are easily obtained, and the fourth, f, can be assumed to be 0.9. If an unknown portion of the electricity is used to power chillers, Zhu (2005) presents a methodology to disaggregate the cooling usage from the rest of the electricity. This disaggregation of cooling load from electricity is beyond the scope of this research, and henceforward it is assumed that cooling is either known or calculable. Beside the products ρc_p and ρh_{fg}, the right-hand side of Equation (13) contains two easily obtained terms, T_{oa} and w_{oa}, and six unknowns: UA_{tot}, $\dot{V}_{oa}$, T_{rm}, w_{cl}, X_{oa}, and q_{lat}. The values of w_{cl} and q_{lat} may be estimated as typical values of 0.009 and $0.5A_F\ Btu/hr$, respectively, where A_F is the total conditioned floor area (assuming 5 people per 1,000 ft^2 and 105 $Btu/(person \cdot hr)$ of latent heat) (ASHRAE 2001).

Summary

In this chapter, the first step in the development of a pre-screening methodology—determining useful parameters—is discussed. Also presented is the theory behind the use of energy balance as the basis for the pre-screening procedure. The actual procedure itself and the tools with which to perform the procedure are covered in the next chapter, and the results of applying this procedure to a sample set of buildings are discussed in Chapter V.

CHAPTER IV

DESCRIPTION OF THE PRE-SCREENING METHODOLOGY

Introduction

The application of the pre-screening methodology presented in this thesis involves obtaining and inserting the data, performing the analysis, and interpreting the results. The chapter begins with a general description of the pre-screening methodology, including its key goals and the tools developed for applying this methodology. The chapter then details the actual procedure to be performed by the user. Precautions for preventing incorrect calculations are included next, followed by a chapter summary.

General Description

In order to find the combined $UA_{tot} + \rho c_p \dot{V}_{oa}$ value, a process is defined to graphically "calibrate" the energy balance model of the building given by Equation (13). Hereafter, the term energy balance load, or E_{BL}, will be used as defined in Shao (2005):

$$E_{BL} = Q_H - Q_{C,tot} + fQ_{ele}. \tag{16}$$

This will be considered the measured energy balance load, $E_{BL,m}$, since it uses the measurable variables on the left-hand side of Equation (13). Designating the right-hand side of Equation (13) as the calculated energy balance load, $E_{BL,c}$, the goal becomes to equate $E_{BL,c}$ with $E_{BL,m}$. The process used to accomplish this is described in this section.

The pre-screening tool was developed in Microsoft® Office Excel to make use of its spreadsheet and graphing capabilities. The pre-screening tool's Excel user interface consists of one primary input worksheet, or spreadsheet, and five charts. All of these sheets comprise a workbook, and one workbook contains the entire analysis for one building. The input spreadsheet contains all the data and numerical output and the energy balance load plot is the primary plot used for this methodology. The remaining four charts—cooling and heating vs. outside air temperature, cooling and heating vs. time, electricity vs. time, and electricity vs. outside air temperature—are included for reference only as supplemental information. These plots can serve as stand-alone information or as pre-formatted starting points for similar plots. The series may be changed, added, or deleted, or the entire plot may be copied and placed next to the original chart sheet. Examples of these charts are shown in Figure 1 – Figure *4*, and the input/output of the input spreadsheet is shown in Figure 5.

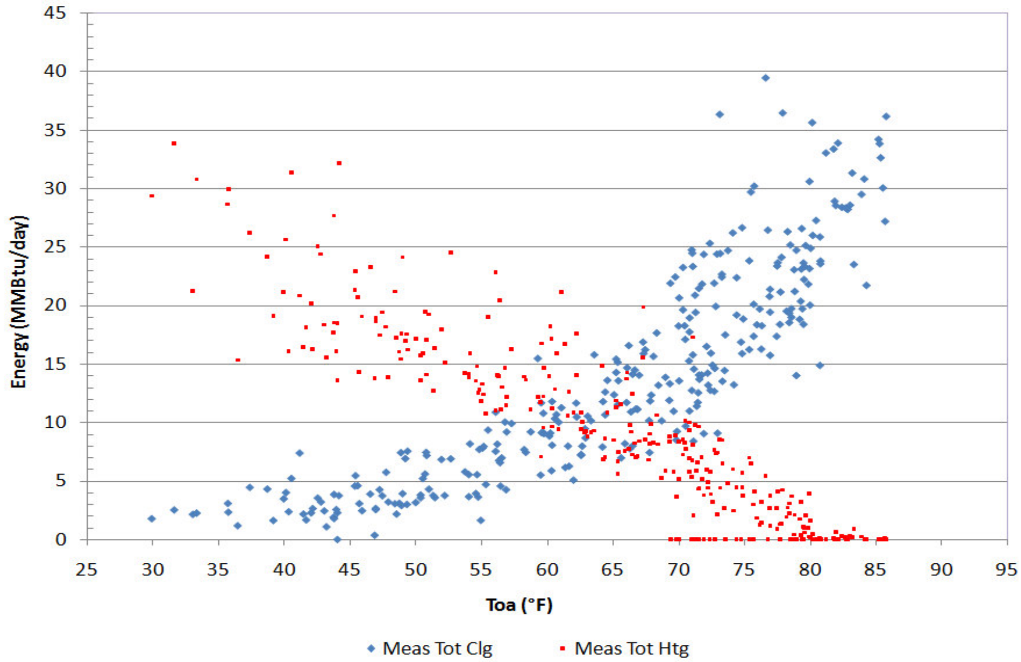


Figure 1 *Example of a cooling and heating vs. outside air temperature reference plot.*

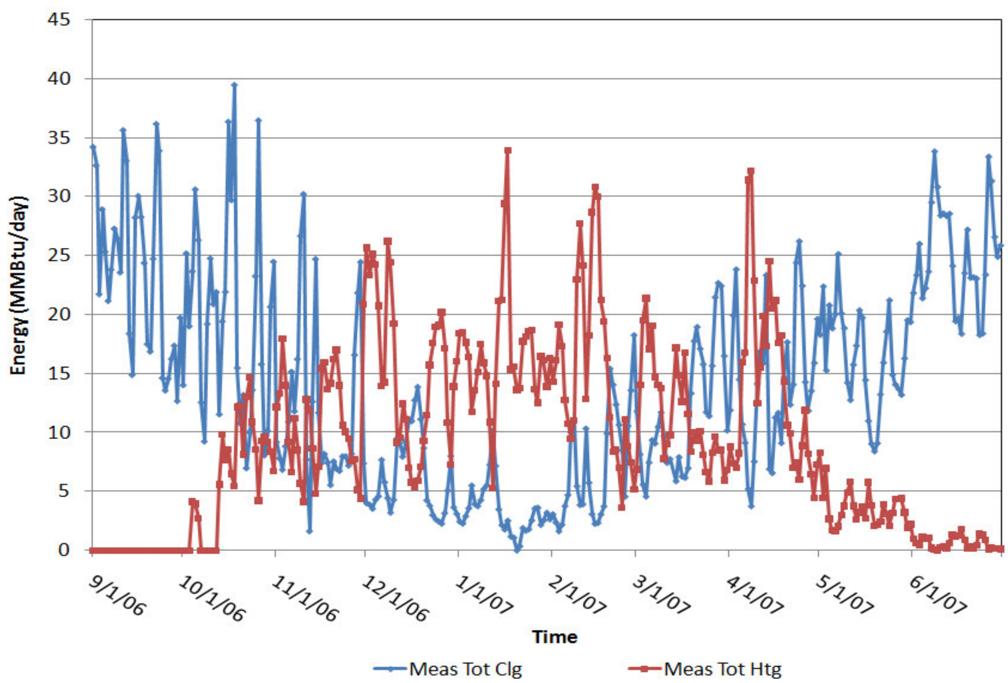


Figure 2 *Example of a cooling and heating vs. time reference plot.*

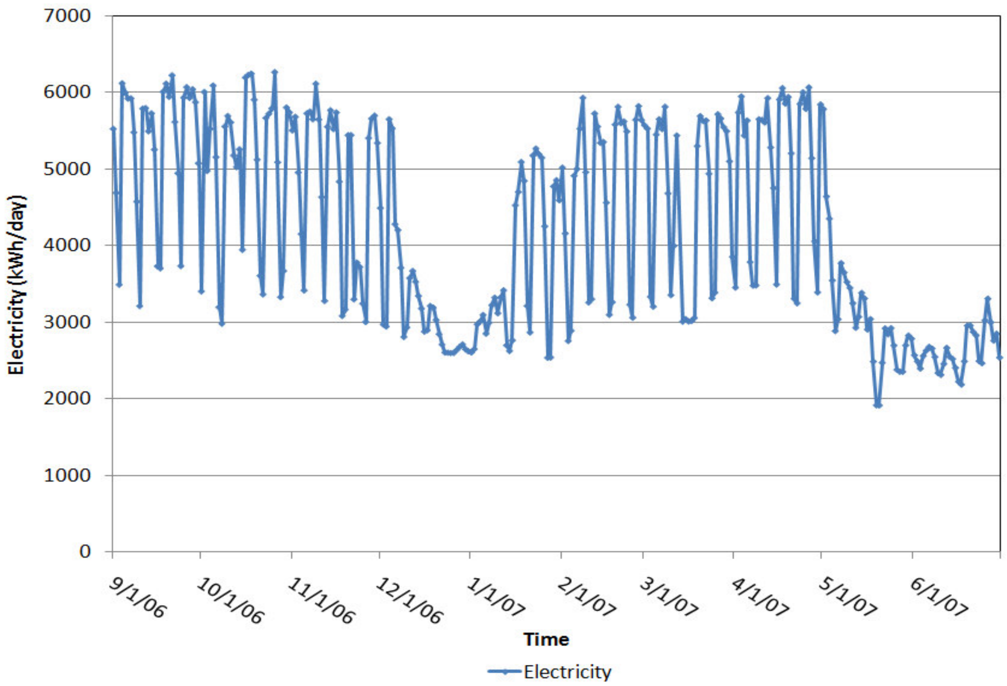


Figure 3 *Example of an electricity vs. time reference plot.*

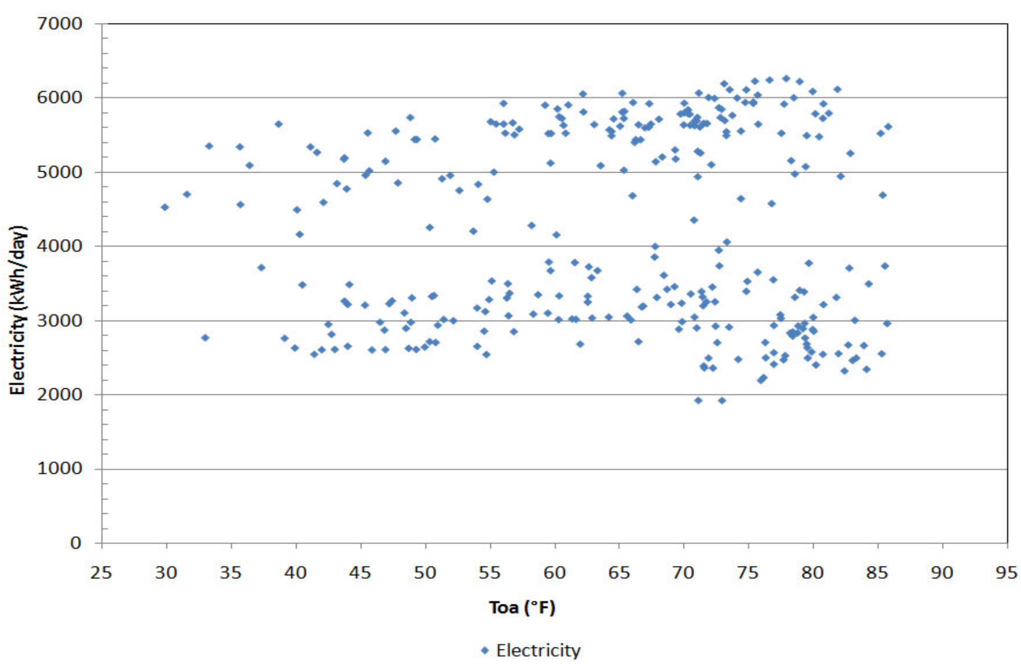
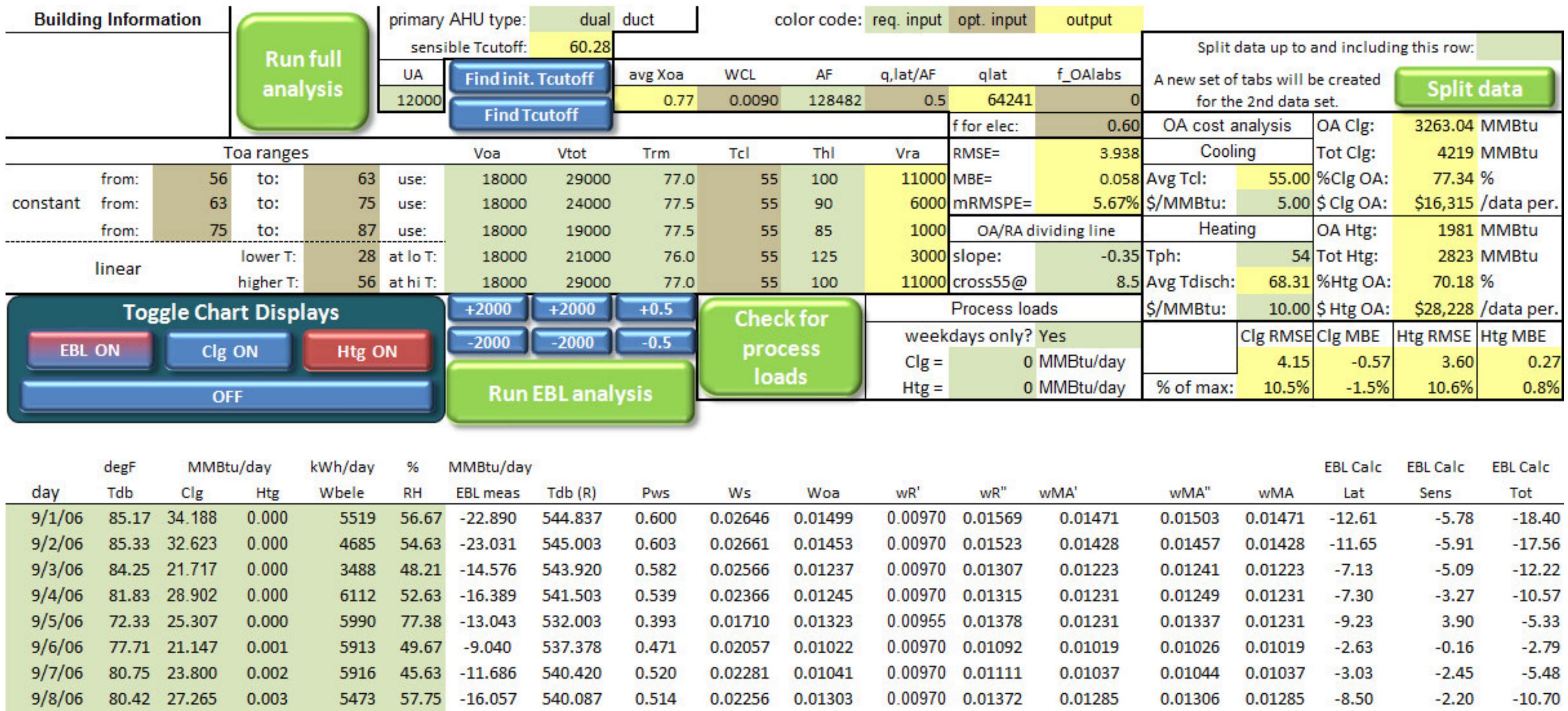


Figure 4 *Example of an electricity vs. outside air temperature reference plot.*



	degF	MMBtu/day		kWh/day	%	MMBtu/day										EBL Calc	EBL Calc	EBL Calc
day	Tdb	Clg	Htg	Wbele	RH	EBL meas	Tdb (R)	Pws	Ws	Woa	wR'	wR"	wMA'	wMA"	wMA	Lat	Sens	Tot
9/1/06	85.17	34.188	0.000	5519	56.67	-22.890	544.837	0.600	0.02646	0.01499	0.00970	0.01569	0.01471	0.01503	0.01471	-12.61	-5.78	-18.40
9/2/06	85.33	32.623	0.000	4685	54.63	-23.031	545.003	0.603	0.02661	0.01453	0.00970	0.01523	0.01428	0.01457	0.01428	-11.65	-5.91	-17.56
9/3/06	84.25	21.717	0.000	3488	48.21	-14.576	543.920	0.582	0.02566	0.01237	0.00970	0.01307	0.01223	0.01241	0.01223	-7.13	-5.09	-12.22
9/4/06	81.83	28.902	0.000	6112	52.63	-16.389	541.503	0.539	0.02366	0.01245	0.00970	0.01315	0.01231	0.01249	0.01231	-7.30	-3.27	-10.57
9/5/06	72.33	25.307	0.000	5990	77.38	-13.043	532.003	0.393	0.01710	0.01323	0.00955	0.01378	0.01231	0.01337	0.01231	-9.23	3.90	-5.33
9/6/06	77.71	21.147	0.001	5913	49.67	-9.040	537.378	0.471	0.02057	0.01022	0.00970	0.01092	0.01019	0.01026	0.01019	-2.63	-0.16	-2.79
9/7/06	80.75	23.800	0.002	5916	45.63	-11.686	540.420	0.520	0.02281	0.01041	0.00970	0.01111	0.01037	0.01044	0.01037	-3.03	-2.45	-5.48
9/8/06	80.42	27.265	0.003	5473	57.75	-16.057	540.087	0.514	0.02256	0.01303	0.00970	0.01372	0.01285	0.01306	0.01285	-8.50	-2.20	-10.70

Figure 5 *Portion of the template input spreadsheet showing the input/output area. Only the first eight days of data are shown. Also, only 19 of the 50 occupied columns are shown.*

Upon plotting both the measured and calculated E_{BL}s against outside air temperature, an inverse parameter identification process may be utilized to determine $UA_{tot} + \rho c_p \dot{V}_{oa}$ and . . This is accomplished by adjusting the parameters in the expression for calculated E_{BL} until it approximately matches the measured E_{BL}.

Procedure

The pre-screening methodology procedure involves three steps, outlined here and each fully described later in this section:

(1) Collect and insert data.

(2) Estimate required building parameters.

(3) Adjust UA_{tot} and $\dot{V}_{oa}$ until $E_{BL,c}$ and $E_{BL,m}$ slopes are approximately the same.

Step 1: Collect and insert data

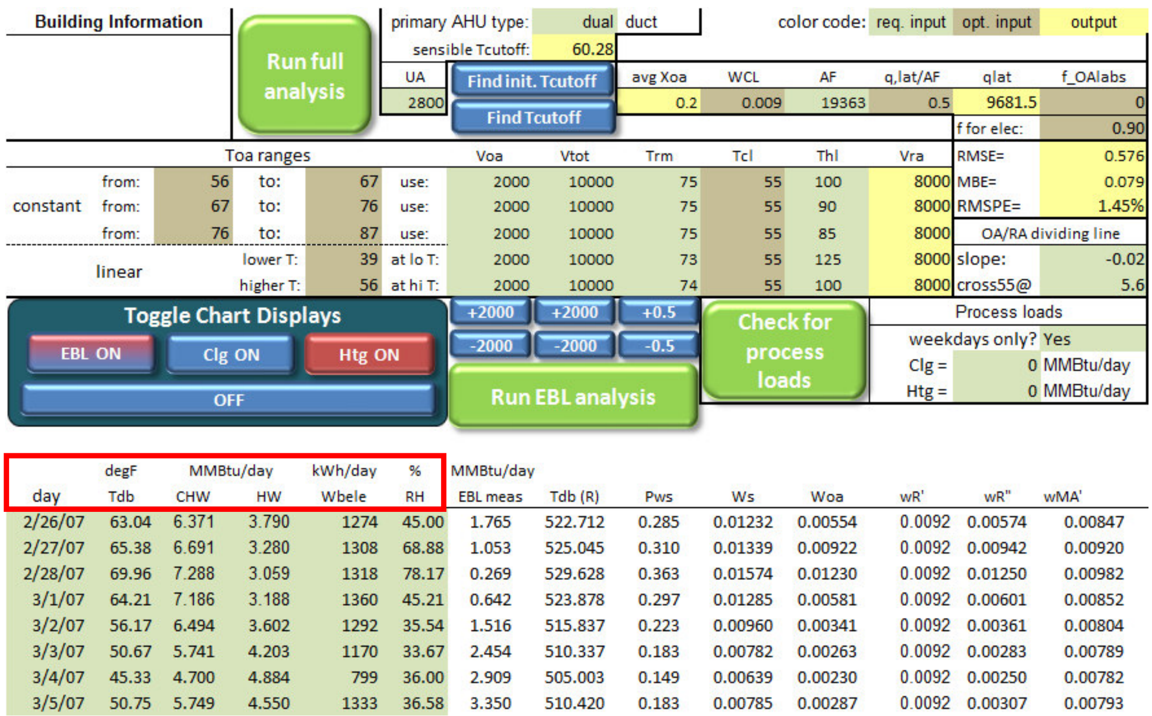
As per the objective, the methodology should enable the engineer to glean as much knowledge and understanding of the building's energy performance and savings opportunities as possible from reasonably easily obtained information. This information must include whole-building electricity, heating energy, cooling energy (if separate from electricity), and weather data for the building's location. Ideally, a full year of data should be collected, but the methodology works for any length of time.

The electricity, heating, and cooling may be obtained from utility bills (for monthly data), a more detailed (hourly or daily) record of energy consumption available from the utility company, a building automation system (BAS) with historical data, or installed, calibrated meters with data loggers. Approximate floor area may be obtained from the building owner or maintenance staff. Weather data (temperature and relative humidity or wet-bulb temperature) may be obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC 2008).

This methodology works with any time period for which data is available—hourly, daily, monthly, or any other longer or shorter time period. The shorter the time period is, however, the more accurate the results will be because of the smaller effect the simplifying assumptions have on the analysis. For example, if monthly data is used, all temperatures and air flow rates are assumed to be constant for a month; in reality, most or all of these parameters vary throughout the month. The same is true for days and even hours, but the changes in shorter time periods are smaller than those for longer time periods. There is a small penalty in calculation times on personal computers for using shorter time periods, with complete analysis calculation times increasing from less than one second to about ten seconds to about twenty minutes for monthly, daily, and hourly data, respectively.

Following the objectives of this research, namely that this methodology should reduce the overall time required for a Continuous Commissioning Assessment, using hourly data in the primary analysis is not practical. If daily data are not available, monthly data works as well, with the same equations and the same steps still applying.

The energy consumption and weather data are inserted into the first six columns of the input spreadsheet under the appropriate headings. The data must be inputted in the specified units or miscalculations will occur. A portion of this spreadsheet is shown in Figure 6.



	degF	MMBtu/day		kWh/day	%	MMBtu/day							
day	Tdb	CHW	HW	Wbele	RH	EBL meas	Tdb (R)	Pws	Ws	Woa	wR'	wR"	wMA'
2/26/07	63.04	6.371	3.790	1274	45.00	1.765	522.712	0.285	0.01232	0.00554	0.0092	0.00574	0.00847
2/27/07	65.38	6.691	3.280	1308	68.88	1.053	525.045	0.310	0.01339	0.00922	0.0092	0.00942	0.00920
2/28/07	69.96	7.288	3.059	1318	78.17	0.269	529.628	0.363	0.01574	0.01230	0.0092	0.01250	0.00982
3/1/07	64.21	7.186	3.188	1360	45.21	0.642	523.878	0.297	0.01285	0.00581	0.0092	0.00601	0.00852
3/2/07	56.17	6.494	3.602	1292	35.54	1.516	515.837	0.223	0.00960	0.00341	0.0092	0.00361	0.00804
3/3/07	50.67	5.741	4.203	1170	33.67	2.454	510.337	0.183	0.00782	0.00263	0.0092	0.00283	0.00789
3/4/07	45.33	4.700	4.884	799	36.00	2.909	505.003	0.149	0.00639	0.00230	0.0092	0.00250	0.00782
3/5/07	50.75	5.749	4.550	1333	36.58	3.350	510.420	0.183	0.00785	0.00287	0.0092	0.00307	0.00793

Figure 6 *Portion of the input spreadsheet. Energy consumption and weather data are entered in the columns whose headings are outlined in red.*

Step 2: Estimate required building parameters

The key variables to be determined— UA_{tot} and $\dot{V}_{oa}$, , and —must have initial estimates in order to run the calculations on the right-hand side of Equation (13). The accuracy of the initial estimates does not affect the final estimates, only the time it takes to reach them. The value of UA_{tot} depends upon the size and geometry of the building, as well as the materials used in the envelope, and as such can vary widely, but 10,000

$Btu/(hr \cdot °F)$ was found to be a suitable starting point for the sample set of buildings used for this research. The outside air ventilation flow rate, $\dot{V}_{oa}$, can be estimated as $0.1A_F$ cfm, assuming 5 people per 1,000 ft^2 and 20 cfm per person, as per ASHRAE Standard 62-2001 (ASHRAE 2001).

Step 3: Adjust UA_{tot} and $\dot{V}_{oa}$ until $E_{BL,c}$ and $E_{BL,m}$ slopes are approximately the same

As the expression for calculated sensible energy balance load, given by

$$E_{BL,c,sens} = \left(UA_{tot} + 1.08\dot{V}_{oa}\right)(T_{rm} - T_{oa}), \tag{17}$$

shows, the slope of the line is $-\left(UA_{tot} + 1.08\dot{V}_{oa}\right)$. Fitting the measured sensible energy balance load with a linear trendline yields a certain slope m in the equation

$$E_{BL,m,sens} = mT_{oa} + b, \tag{18}$$

where b is the intercept of the line, $E_{BL,m,sens}$ is in MMBtu/day, and T_{oa} is in °F (and so m has the same units as the slopes in the equations displayed in plots). The slopes of calculated and measured sensible E_{BL}s are shown in the E_{BL} plot in colors coded to the data points and the legend—light blue for $E_{BL,m,sens}$ and light green for $E_{BL,c,sens}$. The primary metric for determining how well $E_{BL,c}$ and $E_{BL,m}$ match is the root mean square error (RMSE). The RMSE is calculated by the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(E_{BL,ci} - E_{BL,mi}\right)^2}{n}}. \tag{19}$$

Other metrics used are the mean bias error (MBE), given by

$$MBE = \frac{\sum_{i=1}^{n}\left(E_{BL,ci} - E_{BL,mi}\right)}{n}, \tag{20}$$

and a modified root mean square percentage error (mRMSPE), given by

$$mRMSPE = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{E_{BL,ci}-E_{BL,mi}}{E_{BL,m,max}-E_{BL,m,min}} \times 100\right)^2}{n}}. \tag{21}$$

The mRMSPE is a modification of the RMSPE, given in Hyndman and Koehler (2005) as

$$RMSPE = \sqrt{mean(p_t^2)}, \tag{22}$$

where

$$p_t = 100\frac{e_t}{Y_t}, \tag{23}$$

e_t is the difference between measured and calculated values, Y_t is the measured value, and t is the index of the value number. The RMSPE is modified because the measured energy balance load can be negative as well as positive, and values close to zero would artificially raise the error rather than provide a sense of scale. The total range is therefore used instead of the measured value.

At this point in the process, the error expressions may be referenced by the user in order to reduce the residual between $E_{BL,c}$ and $E_{BL,m}$, shown in pink in , as much as possible. The objective is to minimize the RMSE; Step 6 may need to be revisited in order to do so. The RMSE takes into account the scatter in the data, but does not indicate which way the estimated, or calculated, value is biased in relation to the measured value. The MBE, given by Equation (20), is the average difference between calculated and measured values, and it does indicate if the calculated values are, on average, higher or lower than measured values. The MBE should be as close to zero as possible. A positive MBE means that calculated values are too high; a negative MBE indicates calculated values are, on average, lower than measured values. The modified RMSPE is similar to the RMSE except that the former expresses the error as a percentage of the maximum range of measured E_{BL}s. This makes error comparison between buildings practical, whereas RMSE comparison between buildings with energy consumption magnitudes on different scales is meaningless.

Summary

This chapter presented the tools used in the application of the pre-screening methodology introduced in this thesis, as well as the application procedure. The next chapter, Chapter V, presents the results of performing this procedure on a sample set of buildings.

CHAPTER V

RESULTS AND DISCUSSION

Introduction

The pre-screening methodology presented in this thesis was applied to three buildings on the Texas A&M University campus in College Station, TX. The results and conclusions of these analyses are presented in this chapter.

The buildings include Duncan Dining Hall, a large dining facility with a commercial kitchen; Sanders Corps of Cadets Center, a small museum and office building; and the Veterinary Medicine Large Animal Hospital, a two-story building with animal medical care facilities, offices, and classrooms. Each building had been previously assessed as part of the Continuous Commissioning process, and basic information about the buildings and their HVAC system operation before CC was recorded. The conclusions reached through the pre-screening methodology were examined in light of observations and conclusions made by CC engineers to see if they were the same. Observations are discussed in this chapter. Daily energy consumption and historical weather data over various lengths of time before CC were used for all buildings.

Duncan Dining Hall

Duncan Dining Hall is a student dining facility on Texas A&M University's campus that consists of dining and food preparation areas, a bakery, and offices. It has a main floor, a basement, and a mezzanine floor. The total floor area is approximately 128,482 and the building's AHUs are single-duct constant volume (ESL 2008a). The pre-screening procedure defined in Chapter IV was performed on daily Duncan Dining Hall data from September 1, 2006 through June 30, 2007.

The energy balance load plot with minimized RMSE is shown in Figure 7. The RMSE was about 3.9 MMBtu, and the modified RMSPE was 5.7%. The MBE was less than 0.06 MMBtu, and the residual, shown in pink in Figure 7, is centered about approximately the horizontal axis as a result.

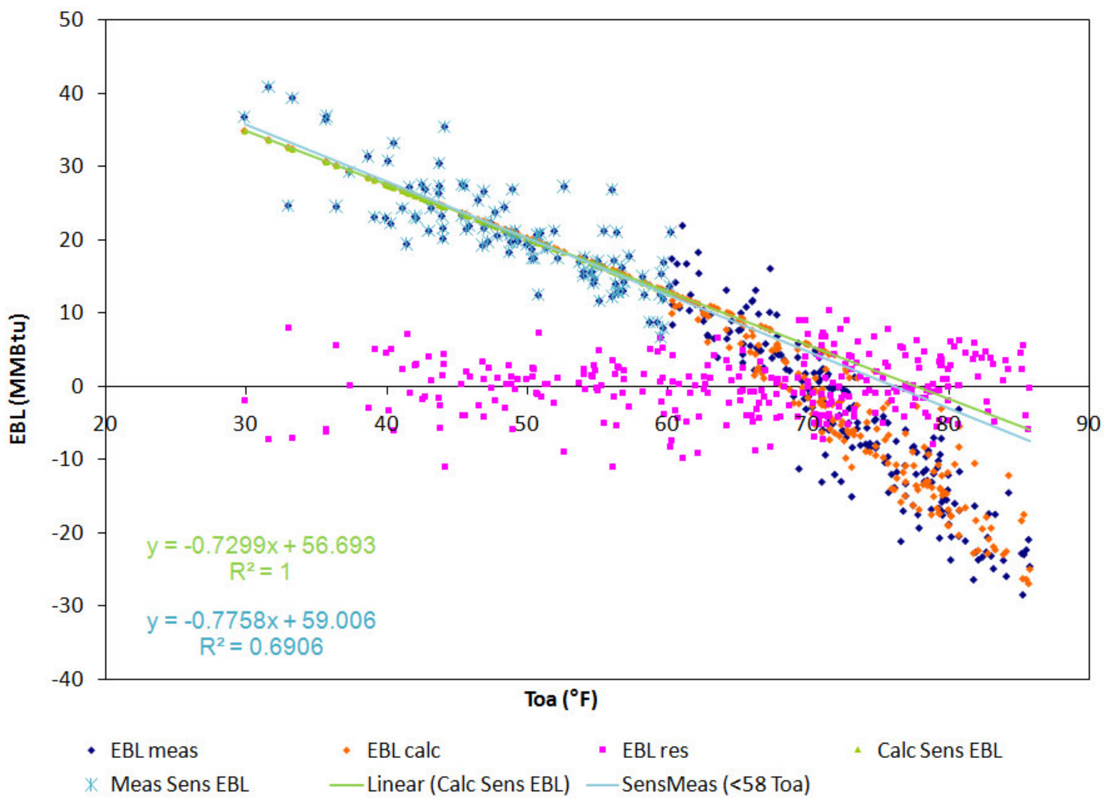


Figure 7 $\boldsymbol{E_{BL}}$ *plot for Duncan Dining Hall with minimized RMSE.*

Another important observation can be made from the electricity vs. time reference plot, shown in Figure 8. The pattern in electricity consumption can give an idea of the building's occupancy patterns if it has not yet been established or if that information was not provided by building owners. The pattern for Duncan Dining Hall is clear for the fall and spring semesters: four consecutive days at peak values, followed by a day with a decrease of about one-third the difference between maximum and minimum values, followed by two days at minimum values. These correspond to Monday through Thursday, Friday, and the weekend, respectively. Christmas break, spring break, and summer break are also easily identified in the plot. A reasonable conclusion is that occupancy approximately coincides with electricity use; if this was found not to be the case, the cause for erratic electricity consumption could be investigated as a potential source for energy savings.

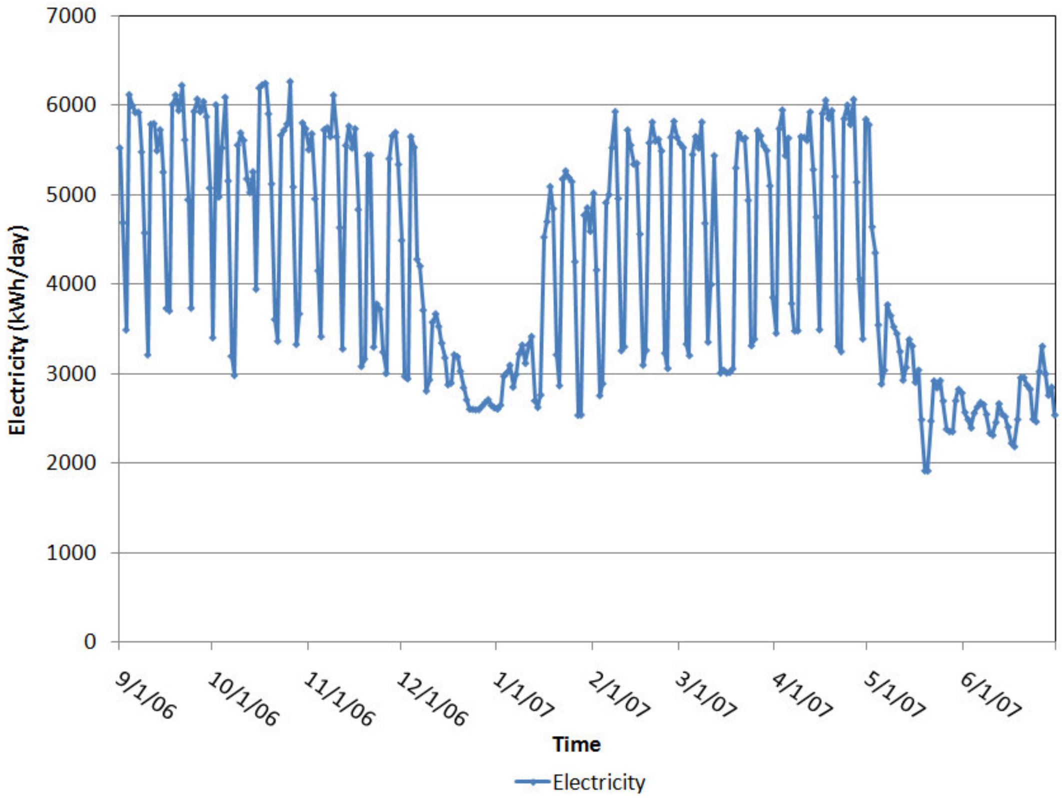


Figure 8 *Electricity vs. time plot for Duncan Dining Hall.*

The dining and food preparation was reported to be generally occupied during the fall and spring semesters from 6:00 AM until 8:30 PM Monday through Thursday, and from 6:00 AM until 2:30 PM on Fridays. The bakery is in operation from 2:00 AM until noon on weekdays (ESL 2008a). The closure for dinner on Friday corresponds with the decreased value of measured electricity noted on Fridays, and the unoccupied periods on weekends and breaks correspond to the minimum values. The peak values therefore correspond to Monday through Thursday, days with the longest occupancy period. This partitioning of the electricity data is illustrated in Figure 9.

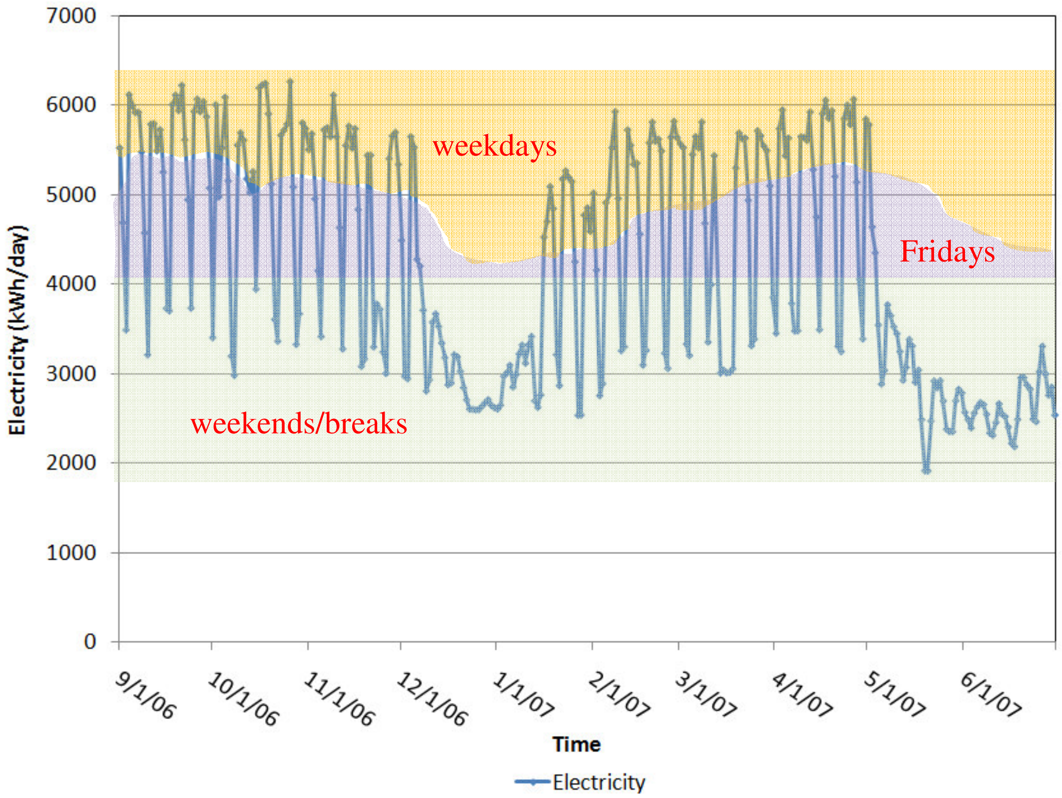


Figure 9 *Electricity vs. time plot for Duncan Dining Hall showing the different types of days by occupancy.*

In conclusion, the pre-screening methodology was able to identify several properties of Duncan Dining Hall. The combined value of $UA_{tot} + \rho c_p \dot{V}_{oa}$, was found to be about 31,000 $Btu/(hr \cdot °F)$ through the pre-screening methodology. This value was deemed reasonable after site observations. Also, the occupancy schedule was also correctly observed by examining the electricity vs. time plot.

Sanders Corps of Cadets Center

The Sanders Corps of Cadets Center is a one-story building on Texas A&M University's campus that houses a museum, a small library, offices, and conference and reception rooms. The total floor area is 19,363 ft^2 and the building is served by one single-duct, variable volume AHU with terminal reheat (ESL 2008b). Daily data from February 26, 2007 through July 21, 2007 was used for the analysis.

The energy balance load plot with minimized RMSE is shown in Figure 10. The RMSE was 0.56 MMBtu, representing about 6.8% of the maximum measured E_{BL} spread. The MBE was 0.018 MMBtu.

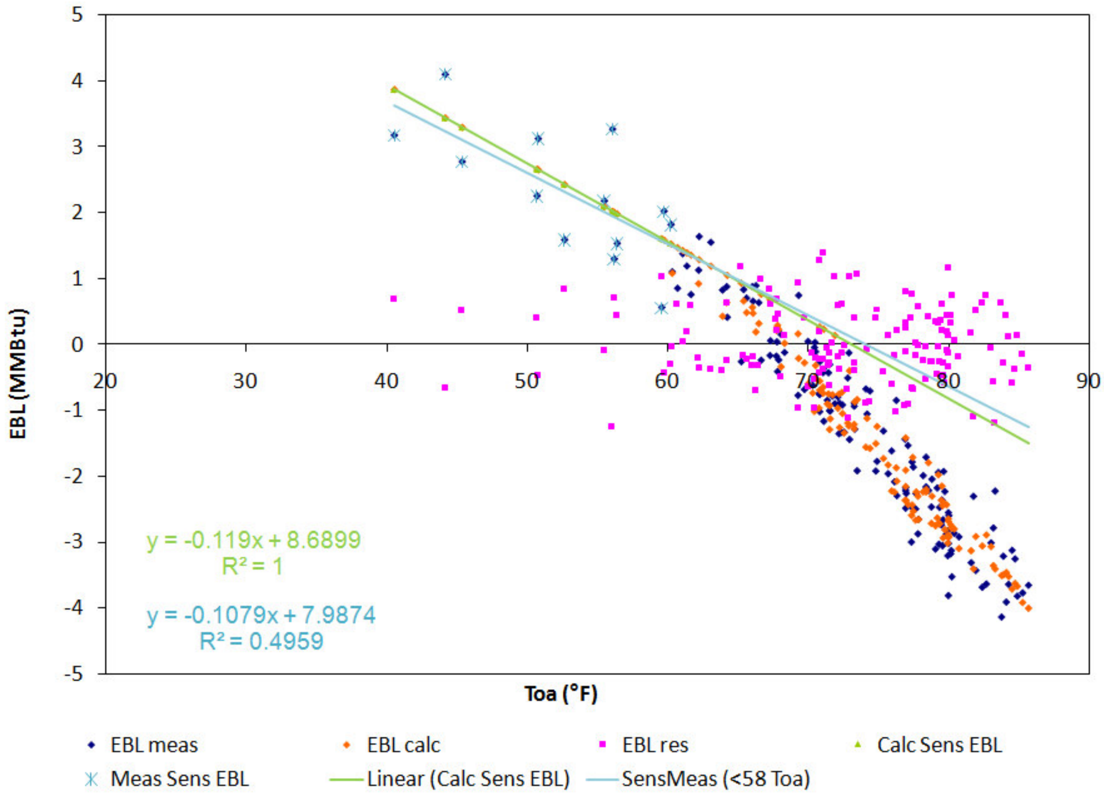


Figure 10 ***E_{BL}*** *plot for Sanders Corps of Cadets Center with minimized RMSE.*

The occupancy schedule can be gathered from Figure 11: generally occupied on weekdays and generally unoccupied on weekends. It was confirmed that the building is generally occupied from 8:00 AM until 5:00 PM on weekdays (ESL 2008b).

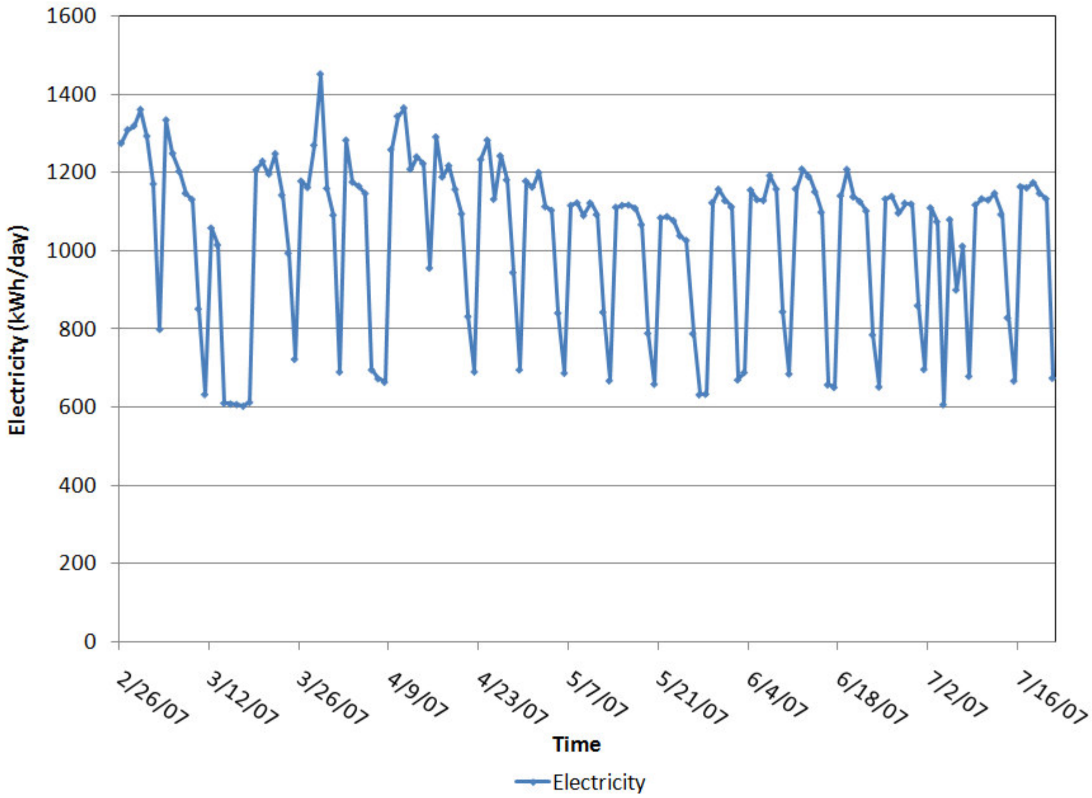


Figure 11 *Electricity vs. time plot for Sanders Corps of Cadets Center showing the weekday peaks and weekend decreases in electricity use.*

In conclusion, the combined value of $UA_{tot} + \rho c_p \dot{V}_{oa}$, was found to be about 5,000 $Btu/(hr \cdot$ °F) through the pre-screening methodology. Site observations led to the conclusion that this value is reasonable for this building. Secondly, the schedule was easily and correctly observed in an automatic already-formatted plot. Thirdly, the pre-screening tool's indications that the fraction of electricity contributing to the building load were reinforced by observations made at the building and further information about the HVAC equipment.

Veterinary Medicine Large Animal Hospital

The Veterinary Medicine Large Animal Hospital (VMLAH) primarily consists of equine medical and surgery wards, equine exam rooms, a food animal complex, an intensive care unit, a pharmacy, a radiology section, veterinary classrooms, and offices. The total floor area is 140,865 ft^2 and the HVAC systems include seven single duct variable volume AHUs, four constant volume 100% outside air AHUs, and ten fan coil units (ESL 2008c). Daily data from September 1, 2006 through July 31, 2007 was used for the analysis.

The E_{BL} plot with minimized RMSE is shown in Figure 12. The RMSE for this data set was 3.8 MMBtu, representing about 3.7% of the maximum measured E_{BL} range. The MBE was 0.11 MMBtu.

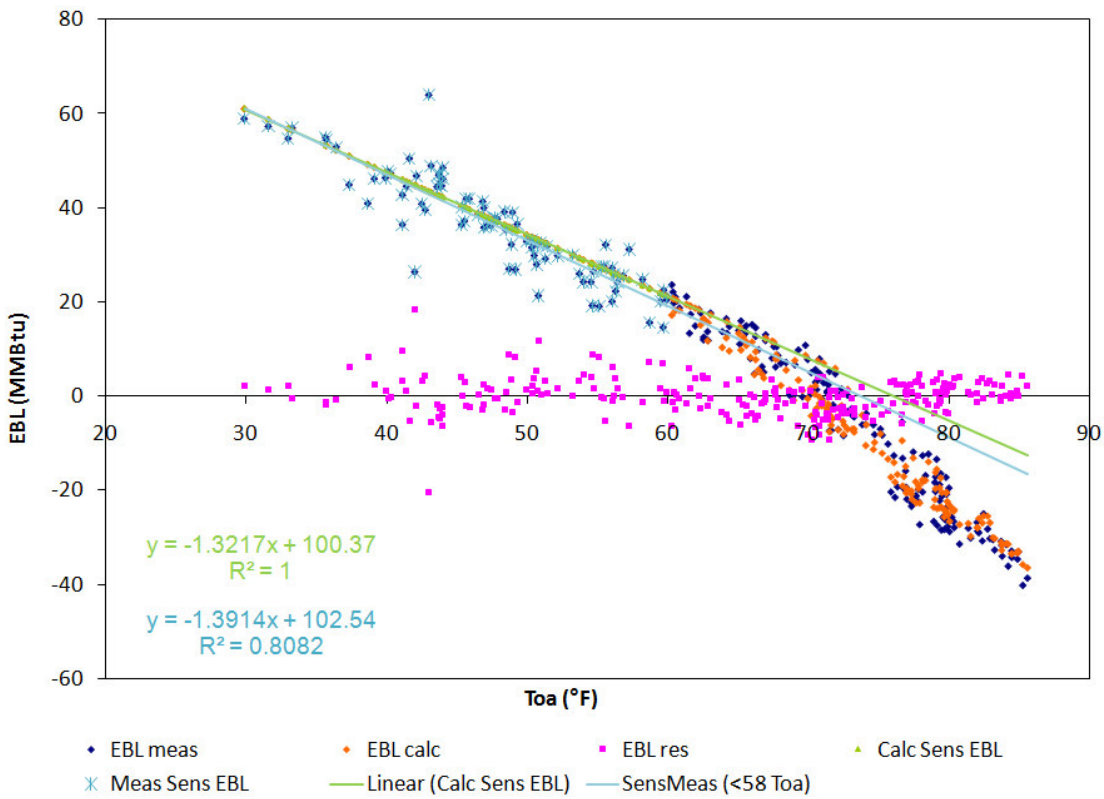


Figure 12 *Energy balance load plot for the Veterinary Medicine Large Animal Hospital with minimized RMSE.*

An important observation can be made from the electricity vs. time plot, shown in Figure 13. This plot shows that there is very little difference—about 7%—between weekday electricity use and weekend electricity use. This means that either the building is being occupied approximately the same amount every day or that most or all HVAC equipment and plug loads remain in use all the time despite dips in occupancy levels. If the latter were later proven to be true, energy could be saved by implementing night and/or weekend setbacks. In this case, all areas of the building were reported to be open all day, every day (ESL 2008c).

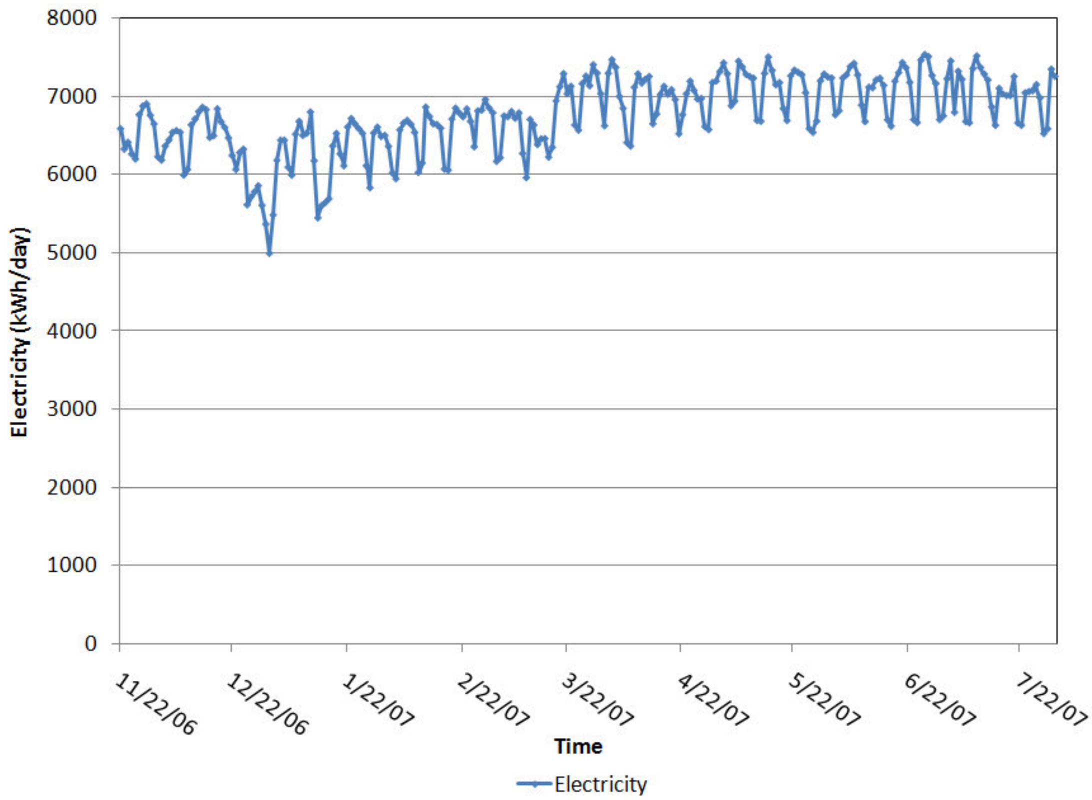


Figure 13 *Electricity vs. time plot for the Veterinary Medicine Large Animal Hospital.*

In conclusion, this tool estimated the combined value of $UA_{tot} + \rho c_p \dot{V}_{oa}$ to be about 54,000 $Btu/(hr \cdot$ °F) through the pre-screening methodology. Site observations confirmed this value to be reasonable. Secondly, a change in operation was easily and successfully identified, since the analysis of each data set resulted in lower errors than that of the combined data set.

Summary

The three case studies presented in this chapter illustrate the utility of the pre-screening methodology developed through this research. The Excel-based pre-screening tool was able to effectively produce reasonable estimates for the combined value of $UA_{tot} + \rho c_p \dot{V}_{oa}$.

In addition to the correct identification of specific parameters, the ready-made approach with pre-formatted plots made the process of examining the data much faster and easier than starting from scratch with a spreadsheet of data.

Table 1 *Summary of errors for the three case studies.*

	Duncan Dining Hall	Sanders Corps of Cadets Center	VMLAH (data after 11/22/06)	Average
EBL RMSE (MMBtu)	3.9	0.56	3.9	2.8
EBL MBE (MMBtu)	0.058	0.018	0.23	0.10
EBL modified RMSPE (%)	5.7%	6.9%	3.7%	5.4%

The errors for the energy balance load, cooling, and heating for all three buildings are summarized in Table 1. As can be seen in the table, the energy balance load RMSE percentages were consistently close to the average of 5.4%.

CHAPTER VI

SUMMARY

In this thesis, a pre-screening methodology to aid in determining potential energy savings in commercial buildings was developed, presented, applied to case study buildings, and discussed. First, the objectives and motivation for this research were stated in Chapter I, followed by a review of the wide range of existing pre-screening methods in Chapter II. Merits and limitations of existing methods were discussed as applicable to the present research.

The steps taken to develop the pre-screening methodology and accompanying Excel-based tool were then detailed in Chapter III. The use of the energy balance method as the basis for the pre-screening methodology was presented.

In Chapter IV, the pre-screening methodology and the tool used to perform the pre-screening were then described in full. The three step procedure was outlined and explained step-by-step.

In Chapter V, three buildings on Texas A&M University's College Station, TX campus served as case studies in the application of the pre-screening methodology. The three buildings were different from each other in many ways: one was a small museum and office building, one a large dining facility with a commercial kitchen, and one a large veterinary medicine hospital with offices and classrooms as well. The results from the pre-screening were presented, explained, and summarized for each building and then all three.

The pre-screening methodology developed and presented in this thesis was able to accomplish its objectives. First, it was self-contained, in that it required no comparison to other buildings or sample sets to provide useful information. Secondly, estimates of the combined value of $UA_{tot} + \rho c_p \dot{V}_{oa}$ were found to be reasonable after site observations. Third, the methodology provides numerous shortcuts and tools via the use of already-formatted tables, plots, and input and output cells. And finally, the pre-screening methodology has been proven to have the potential to provide useful information that can reduce analysis time and consequently reduce the expense of a Continuous Commissioning assessment.

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